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A NOTE ON THE MOVEMENT AND STRUCTURE OF THE FLORIDA HURRICANE OF OCTOBER 1946

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INTRODUCTION

The Florida hurricane of October 6–9, 1946, was distinguished by at least three interesting features:

(*a*) A radiosonde flight was made at Tampa in the eye of the hurricane, the second sounding of its kind in the history of upper air observations.[1]

(*b*) An airplane reconnaissance flight was made over the top of the hurricane cloud system, and motion pictures were taken of the cloud formations during flight.

(*c*) The conditions associated with the extremely rapid intensification and equally rapid dissipation of the storm may be regarded as extraordinary.

It is fortunate that a good number of radiosonde and wind observations were obtained from the storm area. These observations have made it possible to construct a more complete picture of the vertical structure of a tropical cyclone than has been possible before. The subject of hurricane structure is not well understood, and many of the concepts which have been advanced are not satisfactorily substantiated by actual observation. The following note attempts to summarize the salient features of the storm, obtained from all available sources of information, as a possible contribution to future studies of hurricane structure.

INCEPTION OF THE STORM

The intertropical convergence zone in the eastern Pacific Ocean moved northward of its average position during the last week of September 1946, at the same time that an intense extratropical cyclone moved eastward across the United States. One line of convergence crossed the Central American coast as far north as Guatemala, and soon became associated with a surface low pressure system which was elongated in an east-west line and centered over Guatemala. This system persisted from October 1–5, though the surface circulation was negligible during much of the period. Meanwhile, the extratropical cyclone moved out into the Atlantic Ocean and was replaced by a large anticyclone covering most of the United States. Associated with its movement was a pronounced quasi-stationary front or shear line extending from Bermuda southwestward across the Caicos Islands through the Windward Passage and Caribbean Sea to Honduras and Guatemala, where it apparently intersected the intertropical convergence line. As the surface cyclone in the Atlantic moved northeastward, an interesting development occurred in the upper troposphere over the Atlantic: a circular cold-core low pressure system appeared at 30,000 feet southwest of Bermuda. It apparently formed in the trailing southerly portion of the trough associated with the northeastward-moving surface cyclone. On October 4, this upper-level low started moving westward, and on October 5, it was located over Georgia and the Carolinas. As it approached the meridian of the tropical surface low in Guatemala, the latter began moving northeastward and intensifying. Throughout this period the anticyclone over the central United States had successfully blocked all cyclonic intrusions from the west.

The circulation in the tropical low did not become systematic until it started northeastward on the afternoon of October 5. As the low advanced into the Caribbean late on that date, traveling at 18–20 m. p. h., it was still weak and its center poorly defined. Between 0130 and 0730 E. S. T., on October 6, however, the movement slackened to about 12 m. p. h., while the central pressure fell from 1,005 mb. to approximately 993 mb. In this 6-hour period, the low became a circular storm with winds of 50 m. p. h., or more. Eight hours later, on the afternoon of October 6, winds of full hurricane force had been measured by both aircraft and surface vessels.

It is difficult to account for the rapid deepening of the storm. Tropical cyclones forming over Central America at this season generally develop more gradually. Winds-aloft reports were available over the region up to 16,000 feet, but these provided no satisfactory means of determining or measuring horizontal divergence patterns over the storm area. Some contribution to the storm's deepening may have been supplied by the operation of the following factors, which were present when the process took place:

(*a*) Prior to the deepening, cyclonic circulation, or strong cyclonic shear, had been established to high elevations over the incipient surface cyclone.[2]

(*b*) The surface low-pressure system moved out over water at the time of maximum normal diurnal convective activity as well as at the time of the large tropical secondary maximum diurnal pressure fall.

(*c*) The isallobaric conditions associated with the incipient storm may have been reinforced by those of the upper-air low pressure system as the latter moved westward from the Atlantic over the southeastern United States.

MOVEMENT AND STEERING PRINCIPLES

The steering principles ordinarily used in forecasting the direction of movement of tropical cyclones were not easily applied in the case of this storm, since both the field

[1] The first sounding in the eye of a hurricane was made at Tampa at 0600 E. S. T., on October 19, 1944.

[2] In an unpublished paper, "Notes for Guidance of Hurricane Forecasters," W. R. Stevens points out that the development of the surface circulation in cyclones forming in the southwestern portion of the Gulf of Mexico is preceded 48 to 72 hours by cyclonic circulation at 5,000 feet or higher.

of motion and the mean temperature conditions associated with warm-tongue steering (1) were in this instance difficult to analyze. The presence north of the hurricane of the cold-core low pressure system aloft, which had moved into the southeastern United States from the Atlantic Ocean, tended to complicate the upper-air analyses. The circulation of both the cold low and the hurricane extended to high elevations, and it was difficult, with only the rawin data from Miami and Havana available near the storm, to determine the appropriate steering level. Studies made subsequent to the storm's occurrence indicate that it moved parallel to the winds circulating around the upper cold low to the north and not parallel to the

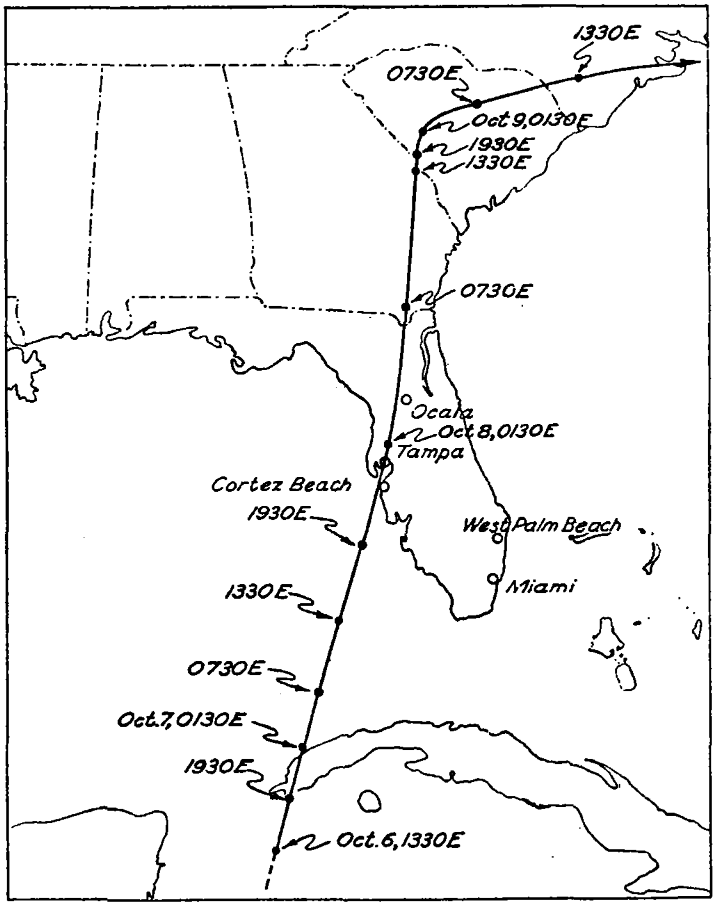

FIGURE 1.—Path of the hurricane, October 6-9, 1946.

axis of the trough extending from this upper low center to the hurricane vortex. Warm-tongue steering patterns were not well defined in the mean temperatures between 700 and 500 mb., because of the initial presence of a tongue of relatively cold air over the southern United States apparently associated with the cold low. This tongue of cold air receded slowly northward along the path of the hurricane. Because of its orientation, the axis of the warm tongue associated with the hurricane could not be located with assurance.

The path of the storm following its development into a major disturbance is shown in Figure 1. The hurricane moved slowly northward at a speed of about 12 m. p. h., until it crossed Cuba. It then began a gradual acceleration to 18 m. p. h., and this speed in turn increased sharply to about 33 m. p. h., when the storm moved inland over Tampa. As it traveled northward into Georgia, a strong high pressure system to the north arrested this rapid motion. It then turned slowly eastward out over the Atlantic. Considering the strong wind movement at all elevations indicated by rawin observations [3] taken at Miami and Havana during its approach and passage, it is puzzling why the storm did not accelerate more rapidly northward before reaching the Florida peninsula. Another apparently anomalous feature of the storm movement is the fact that the greatest filling occurred over water just prior to the greatest acceleration. As the storm passed inland and its speed of movement increased from 18 to 33 m. p. h., the filling stopped abruptly and deepening at a slow rate ensued, as will be discussed later.

STRUCTURE OF THE STORM

A number of regular and special radiosonde releases were made at stations under the influence of this hurricane. One instrument was released at Tampa at 0100 E. S. T., October 8, while that station was in the eye of the storm, and a creditable record was obtained throughout the tropospheric column. This sounding, the other Tampa eye sounding taken during the passage of the similar, though more severe, hurricane of October 1944, and the sounding data obtained from stations in each of the four quadrants of the 1946 storm permitted a more thoroughgoing examination of the thermal structure of hurricanes than had previously been possible.

One means by which the distributions of pressure and temperature in tropical storm vortices may be studied is the pressure anomaly cross section, in which the anomaly is computed from a subtropical standard atmosphere base

[3] Wind observations made by means of radio direction-finding equipment.

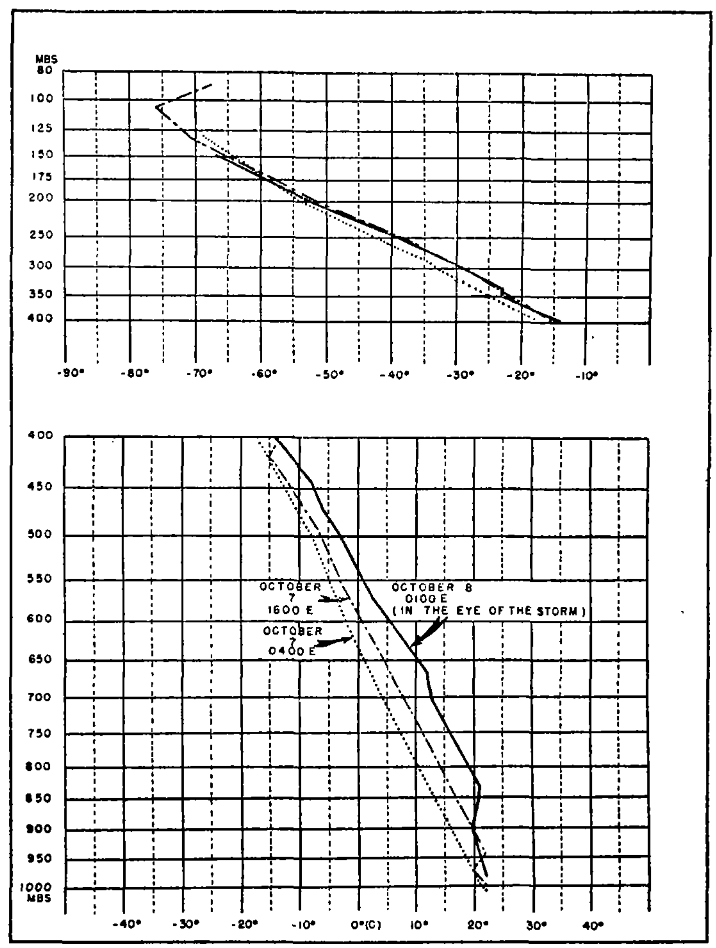

FIGURE 2.—Soundings made at Tampa during the approach and passage of the hurricane.

(2) instead of the U. S. Standard Atmosphere used in connection with altimeter corrections (3). Both space and time cross sections were constructed in the analysis of this 1946 storm. The principal features described below were well marked on each type of cross section, despite the influence of diurnal variations which may have been present in the time cross sections.[4]

Figure 2 contains three soundings made at Tampa during the approach and passage of the hurricane center. The sounding at 0100 E. S. T., was made approximately 30 minutes after the lowest pressure was recorded and while the station was still in the somewhat poorly defined eye of the storm. Figure 3 is a time cross section of pressure anomaly for Tampa during the approach and passage of the storm, while Figure 4 shows the distribution of temperature and relative humidity in time cross section form.

Thermal Structure.—Comparing the soundings shown in Figure 2, it would appear that the core of the storm is

[4] Previous experiences of the author in daily analyses of pressure anomaly cross sections in the tropics have indicated that diurnal variations in the middle and upper troposphere tend to diminish in amplitude over regions of widespread cloudiness.

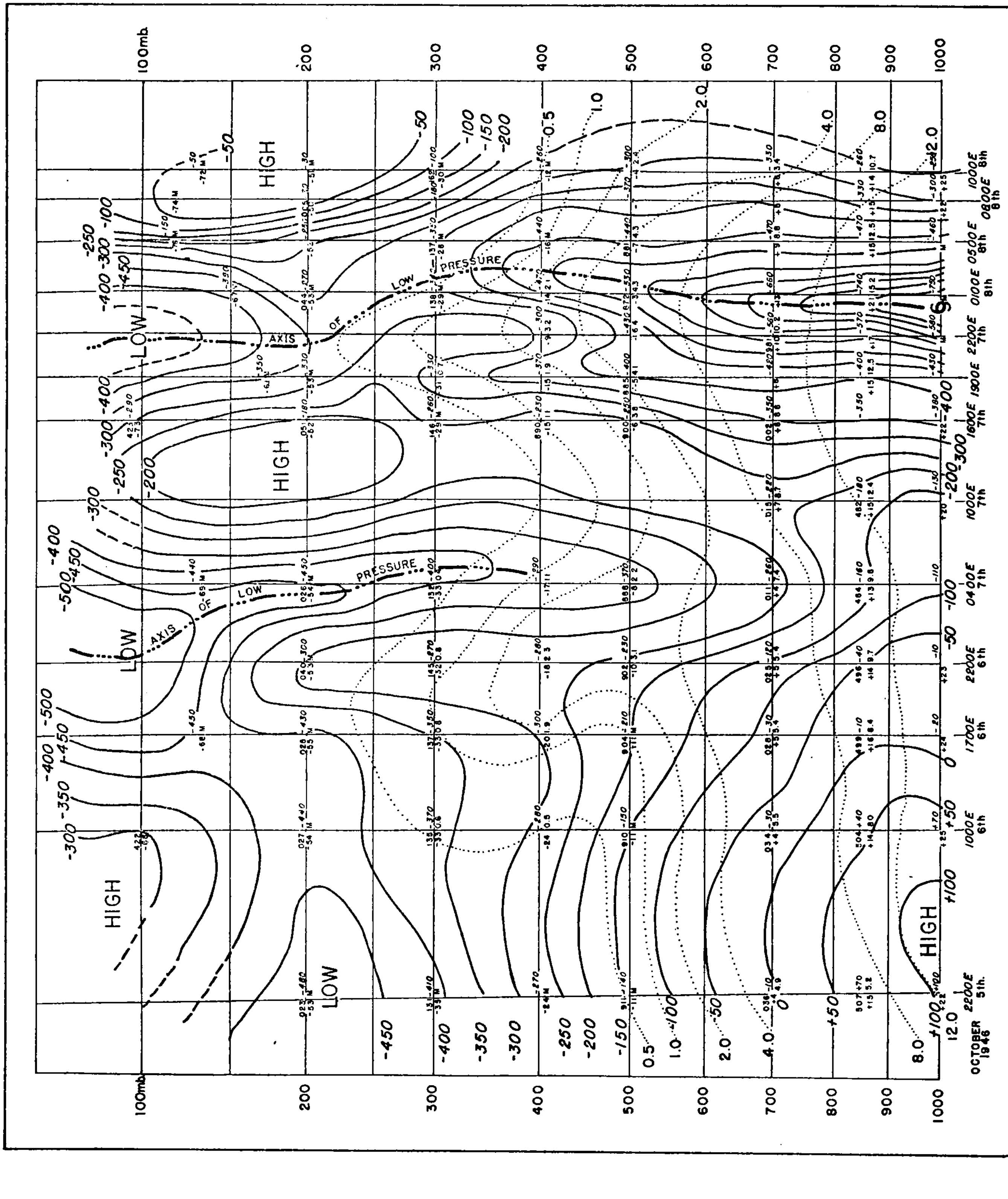

FIGURE 3.—Time cross section of pressure anomaly for Tampa. (Dotted lines, mixing ratio, gm/kgm; heavy dashed lines, extrapolated values of pressure anomaly.)

decidedly warmer at all levels from the surface to approximately 32,000 feet than the air columns at approximately 160 and 340 miles from the center, and slightly colder thereabove. From Figure 4, however, it can be seen that the horizontal temperature gradients represented in Figure 2 by soundings in the eye of the storm and at 9 and 12 hours distant from the eye are not truly representative of temperature gradients immediately adjacent to the eye. The sequence of 3-hourly soundings near the eye indicates that warmest temperatures occur along the axis of lowest pressure from the surface to about 15,000 feet, and in advance of this axis from 15,000 to 30,000 feet. The low thus undergoes a transition from the warm-core type to the cold-core type in this mid-tropospheric region. This transition is also apparent in the pressure anomaly cross section of Figure 3. In this figure, the axis of the low pressure center appears to be truly vertical only in the lower troposphere up to 12,000 to 15,000 feet. In the layer from 15,000 to 20,000 feet, the low-pressure axis seems to be tilted slightly to the rear, or away from the direction of motion. At 25,000 feet the core is displaced approximately 100 miles south of the surface center. Above this level the core assumes a forward inclination until at 40,000 feet it is located about 100 miles north of the surface center.[5] The upper portion of the core seems to be associated in some way with an upper trough of low pressure located at some distance in advance of the storm vortex. The area between this trough and the lower storm vortex is characterized by relatively high pressure and warm, dry air. A similar region of warm, dry air seems to be present at the rear of the storm, giving the impression that the vortex may be surrounded by an annular ring of such air. These features are virtually identical with those exhibited by the soundings made at Tampa during the approach and passage of the hurricane of October 1944.

Airplane reconnaissance reports of the hurricane were examined carefully for significant temperature changes or trends. Because of frequent changes in elevation during the reconnaissance flights it was difficult in most instances to draw definite conclusions, but two flights did yield noteworthy information.

On October 6, a plane entered the northwest quadrant of the hurricane and descended from 1,900 to 600 feet, over a distance of approximately 100 miles, without registering a change in temperature. The plane then remained at an altitude of 600 feet and entered the eye of the storm, circling to the position of lowest pressure. From a point at the very edge of the eye to the position of lowest pressure, the temperature rose 4° C. Conversely, as the plane circled out of the eye into the northeast quadrant, the temperature decreased by an equal amount. At this time the eye, though not well defined, was reported to be approximately 60 miles in diameter.

Almost exactly 24 hours later, on October 7, another plane entered the eye at 500 feet and circled to the point of lowest pressure without recording any distinguishable change in temperature. The temperature of the entire storm core at 500 feet was reported to be approximately the same as that measured the previous day at 600 feet and at the point of lowest pressure.

Wind Structure.—Two rawin reporting stations, Miami and Havana, obtained data extending consistently to high elevations during the progress of this storm. Although several other stations took pilot balloon observations as frequently as possible, these were mostly of short duration because of clouds at low elevations. Considerable wind information was contributed by the reconnaissance airplanes, but because of inconsistencies of wind speeds reported by airplanes reaching the same point in a storm sector within several hours of one another, it was felt that these reports were of greater value in locating the storm center than in determining the variation of wind laterally from the center or the variation with height.

The following is a summary of observed wind variations in the hurricane vortex: As the storm approached Cuba, the Havana rawin observation indicated a slow decrease of wind speed with elevation up to 30,000 feet, with some increases in speed above that level. As the storm approached Miami, which was never closer than 150 miles to the center, the wind above 2,000 feet reached its maximum speed at about 6,000 feet; slowly decreased with elevation to about 10,000 feet; and gradually increased again with elevation. This variation was accompanied by a gradual veering from southeast to east up to 10,000 feet and backing higher aloft to southwest at 30,000 feet. As the storm moved away from Miami, the wind remained uniform to 15,000 feet, increasing slowly with elevation higher aloft. From 2,000–6,000 feet, the wind veered from south to southwest, then slowly backed above that level to south again at 25,000 feet. On October 7, an Army B-29 airplane left West Palm Beach, Fla., on a reconnaissance flight over the top of the hurricane weather. Approaching the storm center from an elevation of 30,000 feet, this airplane reported winds estimated to be "100 m. p. h., shifting rapidly."

Analysis of the high-level patterns was complicated by the presence north of the hurricane of the cold low which had moved in over Georgia and the Carolinas from the Atlantic. The outermost closed isobars of this pressure system extended southward, enclosing the hurricane center at levels above 20,000 feet. At lower levels up to 10,000 feet evidences persisted of the shear line previously mentioned, or the trough associated with the shear line. The result was that the outer isobars of the storm circulation seemed to contain a slight wind discontinuity in the northeast quadrant. This discontinuity continued until the afternoon of October 7, when the storm circulation encompassed the entire Florida peninsula.

After the storm crossed Cuba, strong cross-isobar flow toward lower pressure was noted at Florida stations in the forward quadrants. This flow was so pronounced during the morning of October 7, that the center seemed to be displaced much farther eastward than the pressure data would allow. The flow became more circular at midday and remained so until late afternoon when winds at Florida stations directly ahead and to the left of the advancing storm center assumed an angle of more than 45 degrees to the isobars. Insofar as the available observations indicate, the winds in other quadrants were not directed across the isobars in an unusual manner. As the hurricane moved into the Florida peninsula at Tampa on the night of October 7–8, the heaviest rainfall occurred in the left front quadrant. This circumstance would imply that at low levels the greatest horizontal convergence must have occurred in the left front quadrant. The rainfall at stations in that quadrant amounted to 5–7 inches, most of which fell during heavy thunderstorms occurring several hours before the passage of the storm center.

The band of winds of hurricane force around the storm center probably never exceeded 50 miles in width, although

[5] The radiosonde flights at Tampa were made with conventional receiving equipment rather than the more recently developed SCR-657 direction-finding equipment. It was impossible, therefore, to determine the exact path of the balloon, or to state with assurance that it remained in the eye of the storm throughout the flight, or that it left the eye at any one point. To this extent the verticals upon which the data from each sounding have been plotted may not be truly so. Consequently, the tilt of the storm axis may be somewhat different from that here represented. It is not likely that deviation from vertical ascent during the 60 to 70 minutes required for the flight would exceed the distance of the time axis separating adjacent 3-hourly soundings.

winds of gale force extended outward several hundred miles in the northern semicircle of the storm, and the diameter of the storm circulation ranged up to 750 miles. As the storm moved inland on the Florida coast, a remarkable transition took place near its center. The central area of relative calm became poorly defined and apparently expanded to engulf virtually all of the area previously covered by the hurricane-force winds. There was thus produced a poorly defined and relatively flat center of considerable diameter in which winds increased outward gradually rather than abruptly, reaching gale force at a distance of 75–100 miles from the point of lowest pressure. No station in Florida experienced surface winds in excess of 75 m. p. h.; few reported winds over 60 m. p. h., except in gusts; and the highest wind recorded at Tampa was 47 m. p. h. At the same time, no station seemed to experience the type of calm usually characteristic of the eye of such a storm. Some stations reported winds gradually decreasing from 40–50 m. p. h. down to 15–20 m. p. h. at the time of lowest pressure, then increasing,

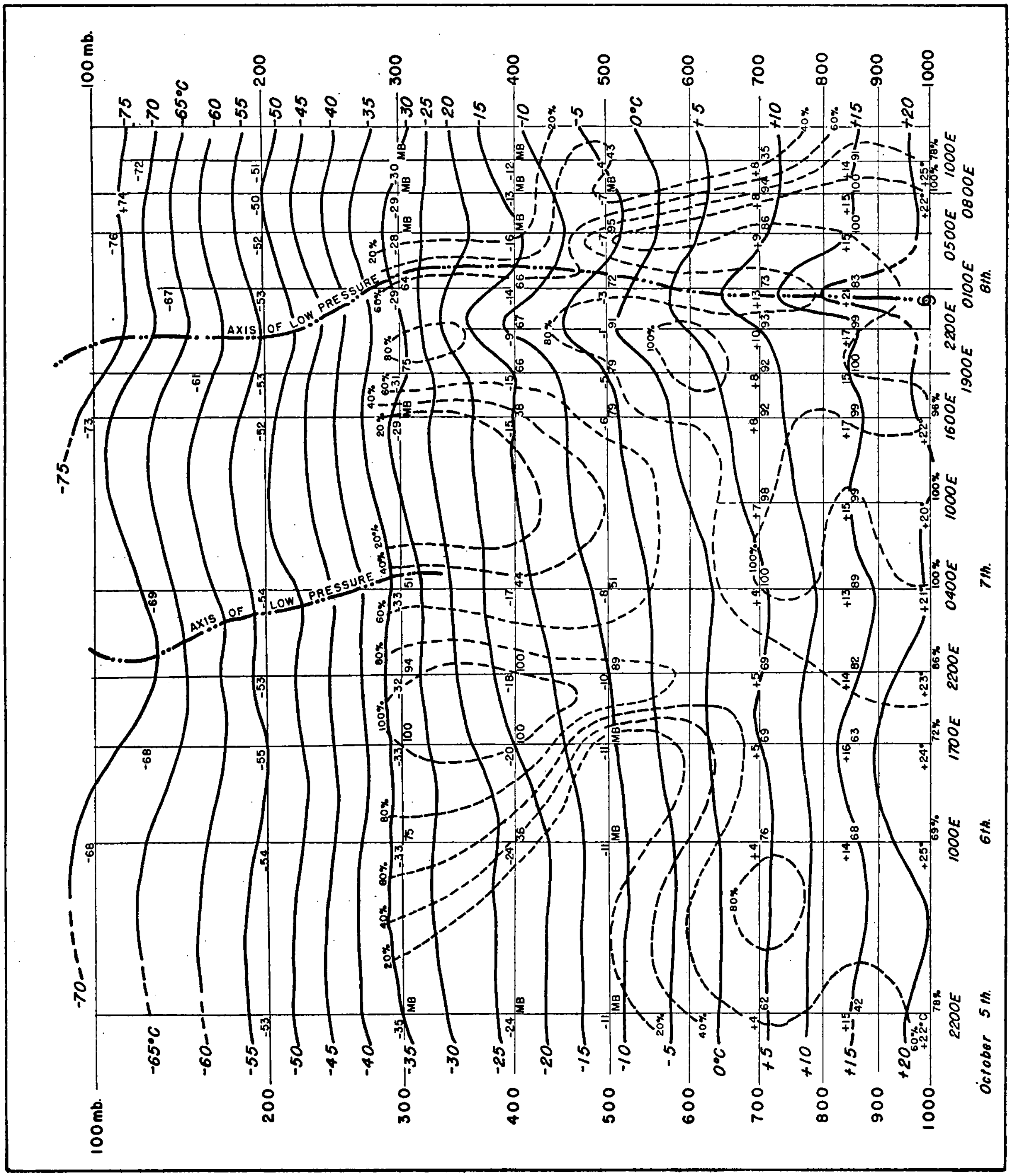

FIGURE 4.—Time cross section showing the distribution of temperature and relative humidity.

without even a relative calm. Other stations reported complete calm for as long as 1 hour, although none reported a rapid transition from near-hurricane-force winds to relative calm. As the storm moved across Florida, surface winds were in general considerably subgradient within 100 miles of the center. A short distance above the surface, however, there seemed to be little disruption of hurricane-force winds near the center. At their times of lowest pressure, several stations reported rapidly moving low clouds, though surface winds were only fresh. One observer stated that while small trees were being gently swayed at the peak of the storm, the tops of taller pines in the same field were being violently twisted and sheared.

The sharp reduction of wind speed at the surface would be more easily understandable if rapid filling had followed the storm's passage inland. Some preliminary filling did occur: the central pressure was reported by a reconnaissance airplane as 978.7 mb., at 1630 E. S. T., on October 7; by Cortez Beach, as 980.4 mb., at 2230 E. S. T., on October 7; and by Tampa, as 986.8 mb., at 0030 E. S. T., on October 8. This tendency toward filling did not continue, however, but ceased abruptly when the center moved farther inland. Ocala, located about 90 miles north-northwest of Tampa, reported 986.1 mb., at 0315 E. S. T., on October 8. In view of these facts, the rapid dissipation of the band of hurricane-force winds as the storm moved inland remains one of its most unusual and puzzling features.

Cloud Structure.—An abundance of cloud data was obtained from airplane reconnaissance, including the observations made by the B-29 airplane which took off from West Palm Beach on October 7, and flew over the storm at elevations ranging from 20,000 to 33,000 feet. Summarization and reconstruction of the data from numerous flights made into the storm revealed the following features which seem to be characteristic of this hurricane:

(*a*) The cirrostratus and altostratus emerging from the storm apparently extended farthest in the direction of storm movement. On the western periphery of the storm the cirrostratus did not extend beyond the wall of low cloudiness.

(*b*) The cirrostratus and altostratus cloudiness extending ahead in the direction of storm movement merged into numerous squalls and shower activity 250 to 300 miles in advance of the storm center. Between this area of showers and the wall of nimbostratus which marked the region of intense storm circulation remarkably little lower cloudiness was present. The base of the cirrostratus and altostratus overcast over this area lowered in the direction of the storm center at the rate of approximately 2,000 feet per 100 miles until it merged in the wall of nimbostratus sometimes referred to as the bar of the storm.[6]

(*c*) In the region of hurricane-force winds, ceilings remained well above 500 feet, and the ocean was obscured only in the heaviest rain.

[6] It is of interest to note that the area of squalls ahead of the storm coincides with the position of the anomaly trough aloft (at 0400 E. S. T., on October 7) on the pressure anomaly cross section of Figure 3. This region of precursory showers and squalls has been observed in connection with similar anomaly troughs aloft in at least three other hurricanes for which sufficient data were available.

(*d*) The eye of the storm was never cloudless, although lower cloudiness was seldom present in sufficient amounts to constitute a ceiling. The wall of clouds surrounding the eye was very nearly vertical, with varying coverages of altostratus and cirrostratus over the top. While the storm was still developing on October 6, the eye was about 60 miles in diameter. Winds did not diminish suddenly as the eye was entered, but gradually fell off from Beaufort force 7 at the outer fringes to force 1 at the point of lowest pressure. At this stage in the storm's development there was no solid wall of low and middle clouds at the southern edge of the eye. Only scattered low fractostratus clouds were reported visible southward of the southern edge of the eye. On October 7, airplane reports described a solid wall of low clouds surrounding a well-defined eye, considerably smaller than reported on the previous day. After passing over Cuba the eye became elongated in the direction of movement. This fact was verified by actual reconnaissance and by radar measurements.

(*e*) Reports from the B-29 airplane flight on October 7, indicate that cumulonimbus towers rose well above the ceiling of the plane near the outer edge of the eye of the storm, with the tops of the clouds forming the overcast in the eye near 20,000 feet. The plane encountered some icing at 20,000 feet in the active storm circulation. No heavy or dangerous turbulence was encountered at any time during the B-29 airplane flight, although a noticeable transition into smoother air was detectable as the plane passed over the eye. The surface center was easily located by radar from flight level near 30,000 feet. Navigation was rendered difficult by extreme radio interference from precipitation static, and all radio direction-finding aids, including Loran, proved ineffective near the storm center. It was impossible to maintain radio contact with ground stations.

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